

$\frac{d}{dt} \left( \frac{\partial L}{\partial v} \right) = \frac{\partial L}{\partial x}$

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**PROGRAM CONTROL FLOW CONDITIONED ON PRESENCE OF  
REQUESTED DATA IN CACHE MEMORY**

**FIELD OF THE INVENTION**

The present invention generally relates to computer systems having cache memories, and more particularly to optimizing program performance in the event of a  
5 cache miss.

**BACKGROUND**

Caches were invented for computer systems to address the problems associated with slow memory access relative to processor speed. Without a cache, the processor  
10 must wait for instructions or operands ("data") from memory in order to proceed with program execution. The time a processor spends waiting essentially wastes processor capacity. With a cache, the long memory access times are eliminated when the requested data are present in the cache.

While memory speeds have improved substantially, the increase in processor  
15 speeds has been far greater. The increase in memory speed means that a processor will wait less (real time) for data to be retrieved from memory. However, the increased processor speed means the processor must wait a greater number of processor cycles in reading the data from memory. Thus, even though a processor may spend less real time waiting for data, the processor may be spending a greater number of cycles waiting  
20 relative to prior generations of processors. While processor speeds have improved, the processors may be spending a greater percentage of time waiting and therefore wasting a greater percentage of processing capacity.

While increased cache sizes reduce the number of times that a process is forced to

wait for data from memory, the increased size alone is not enough to make up for the growing difference in speeds between memories and processors.

A method and apparatus that address the aforementioned problems, as well as other related problems, are therefore desirable.

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### **SUMMARY OF THE INVENTION**

The invention provides method and apparatus for conditioning program control flow on the presence of requested data in a cache memory. In a data processing system that includes a cache memory and a system memory coupled to a processor, in various  
10 embodiments program control flow is conditionally changed based on whether the data referenced in an instruction are present in the cache memory. When an instruction that includes a data reference and an alternate control path is executed, the control flow of the program is changed in accordance with the alternate control path if the referenced data are not present in the cache memory. The alternate control path is either explicitly specified  
15 or implicit in the instruction. In another embodiment, the requested data are not returned to the processor in the event of a cache miss. In yet another embodiment, a probe-cache instruction is used to check for specified data in the cache memory without loading the data into the processor. If the data specified in a probe-cache instruction are not present in the cache memory, the program flow is changed as specified by the instruction.

20 Various example embodiments are set forth in the Detailed Description and Claims which follow.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

Various aspects and advantages of the invention will become apparent upon review  
25 of the following detailed description and upon reference to the drawings in which:

FIG. 1 is a functional block diagram of an example computing arrangement;

FIG. 2 is a flowchart of a process performed for a load-memory instruction where control flow is changed and data are returned to the processor on a cache miss in accordance with one embodiment of the invention;

5           FIG. 3 is a flowchart of a process performed for a load-memory instruction where control flow is changed and no data are returned to the processor on a cache miss in accordance with another embodiment of the invention; and

FIG. 4 is a flowchart of an example process performed for a probe-cache instruction.

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#### **DETAILED DESCRIPTION**

In various embodiments, the invention conditionally alters program flow in the event of a cache-miss condition. This allows the program to schedule an alternative control flow to reduce the performance-degrading effects of memory latency. The invention is useful in a number of scenarios. In one scenario, program control is transferred to an instruction that does not depend on the requested data, and the requested data are read from memory into cache and provided to the processor while one or more other instructions are executed. In another scenario, program control is transferred on a cache-miss condition, and the requested data are returned to the cache but not to the processor. In yet another scenario, a probe-cache instruction is executed to determine whether specified data are present in the cache. If the specified data are present, program execution continues with the next instruction. Otherwise, control is transferred to a specified target address.

FIG. 1 is a functional block diagram of an example computing arrangement. The computing arrangement includes processor 102, cache memory 104, and system memory

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106. In various embodiments, the invention is suitable for use with any of a variety of computing architectures. Generally, processor 102 executes instructions and manipulates data that are stored in system memory 106. Cache memory 104 provides temporary storage of instructions and data that are requested by the processor. While many modern  
5 processors have an on-board first-level cache, for the purposes of this discussion, cache memory 104 refers in function to all the levels of cache in a computing arrangement.

When an instruction executing on processor 102 references data (either a read or write request) from cache memory 104, the cache memory determines whether the referenced data are present. If the data are not present, the cache memory signals a cache-  
10 miss condition to the processor. The signaling of a cache-miss condition, in some designs, causes the CPU to stall until the referenced data are brought into cache memory (for a read request). In "stall-on-use" designs, the cache-miss condition is used to stall only the loading of the register file with the referenced data, and a more global stall of the CPU occurs only if an attempt is made to access the referenced data before the data are returned  
15 to the register file. In both cases, an indication that the data are not present in the cache memory is provided to the processor's control logic.

In the present invention, the special instructions executed by the processor cause a conditional skip or branch in response to a cache-miss condition. By permitting an alternate control flow in the event of a cache-miss condition, the computation cycles of the  
20 processor may be used while the referenced data are retrieved from system memory.

It will be appreciated that there are numerous options for implementing instructions that alter control flow on a cache-miss condition. For example, in a "skip on cache-miss" load instruction, the encoding need only differ from a normal load instruction by a single bit in the operation code. There may be a variety of load instructions in a  
25 typical instruction set (for different data lengths, manipulation of index registers as a side

effect, different destination register files, etc.). Any or all of the different load instructions may have a skip option. In another embodiment, the program control flow is changed by branching. It will be appreciated that there are generally two types of branches. A simple branch transfers control to a target location and does not return control to the branch point.

5 A branch to a subroutine involves a transfer of control to a target location and a provision for subsequent return of control to the branch point.

FIG. 2 is a flowchart of a process followed in execution of an example load-memory instruction, with control flow depending on a cache-miss condition and the referenced data being returned to the cache memory and to the processor. At step 152, the

10 load instruction causes the cache memory to be checked for the referenced data. If the data are present, decision step 154 directs the process to step 156 where program execution continues with loading of the requested data and execution of the instruction that follows the load instruction. It will be appreciated that in a stall-on-use design the loading of the data from the cache and the continued execution of instructions may

15 proceed in parallel, provided that the instructions executed do not depend upon the data being returned.

If the referenced data are not present in the cache memory, decision step 154 directs the process to steps 158 and 162, which proceed in parallel. At step 158, control is transferred to the instruction specified by the load instruction, and while the program

20 execution continues in the alternate control path, the referenced data are loaded from the system memory into the cache memory. When the program can execute no further because of dependencies on the referenced data, at step 160 the process waits for the referenced data to be returned to the processor from the cache memory. At step 164, a signal is generated and provided to the processor when the data are available. If the load-

25 memory resulted from a skip or simple branch instruction, execution may or may not

return to the branch point, depending on the program logic. If, on the other hand, the load-memory instruction resulted from a branch to a subroutine, then control would be returned to the branch point upon execution of a subsequent "return from subroutine" instruction.

FIG. 3 is a flowchart of a process followed in execution of an example load-memory instruction, with control flow depending on a cache-miss condition and the referenced data not being returned to the processor on a cache miss. At step 202, the load instruction causes the cache memory to be checked for the referenced data. If the data are present, decision step 204 directs the process to step 206 where program execution continues with loading of the requested data and execution of the instruction that follows the load instruction. It will be appreciated that in a stall-on-use design the loading of the data from the cache and the continued execution of instructions may proceed in parallel, provided that the instructions executed do not depend upon the data being returned.

If the referenced data are not present in the cache memory, decision step 204 directs the process to steps 208 and 210, which proceed in parallel. At step 208, control is transferred to the instruction specified by the load instruction, and while program execution continues in the alternate control path, the referenced data are loaded from the system memory into the cache memory (step 210). If the load-memory resulted from a skip or simple branch instruction, execution may or may not return to the branch point, depending on the program logic. If, on the other hand, the load-memory instruction resulted from a branch to a subroutine, then control would be returned to the branch point upon execution of a subsequent "return from subroutine" instruction. In another embodiment, the data are not loaded into the cache memory in the event of a cache miss.

FIG. 4 is a flowchart of a process followed in execution of an example probe-cache instruction, with control flow depending on a cache-miss condition. The probe-cache instruction checks the cache for the specified data and conditionally changes program

control flow based on a cache-miss condition without loading any data into the processor or cache memory. At step 252, the load instruction causes the cache memory to be checked for the referenced data. If the data are present, decision step 254 directs the process to step 256 where program execution continues with the instruction that follows the probe-cache instruction. If the referenced data are not in the cache memory, at step 258 program control is transferred to the target address specified by the probe-cache instruction. If the probe-cache instruction is in combination with a skip or simple branch instruction, execution may or may not return to the branch point, depending on the program logic. If, on the other hand, the probe-cache instruction is in combination with a branch to a subroutine, then control would be returned to the branch point upon execution of a subsequent "return from subroutine" instruction.

The present invention is believed to be applicable to a variety of computing architectures. Other aspects and embodiments of the present invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and illustrated embodiments be considered as examples only, with a true scope and spirit of the invention being indicated by the following claims.